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Wideband Directional Coupler for Millimeter Wave Application based on Substrate Integrated Waveguide

Mohammad Javad Tavakoli [a*], Ali Reza Mallahzadeh [a]

[a] *Electrical Engineering Department, Shahed University, Tehran, Iran*

Abstract

Recently, Substrate Integrated Waveguide (SIW) techniques have been noticed for millimeter wave devices in microwave applications. In this paper, we are developing a wide band directional 3 dB coupler with a phase of 90° phase delay in the range of 30-40 GHz based on periodic vias and multi hole structure. For achieving this wide bandwidth multi-section coupler is designed based on the theoretical modeling and the simulation result is compared with HFSS and CST with two different numerical methods show good performance with low insertion and return loss, broad operational bandwidth and high isolation. A fractional bandwidth is about 28.5 %.

Keywords:

Substrate Integrated Waveguide;
Coupler;
Millimeter wave.

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1- Introduction

Recently, Millimeter wave (mm) range has been noticed for its compact size of the devices and less microwave loss in range of Extremely high frequency (EHF) in the electromagnetic spectrum from 30 to 300 gigahertz and the band of 38.6 - 40.0 GHz is implemented for licensed high-speed microwave data links at USA region [1]. In the mm-wave regime, the compromise is often between accurate and expensive CNC or EDM machining of waveguide technology on one hand, and inexpensive but higher-loss SIW circuitry on the other. Moreover, for broadband mm-wave applications, it is often difficult to satisfy all-metal waveguide design specifications as dimensional parameters become too small even for advanced fabrication techniques [2]. Therefore, the SIW is attractive for the extension of microwave and millimeter wave applications such as cavity filters [3], antennas [4], phase shifter [5], power dividers [6] and Diplexers [7].

In the other hand, the substrate integrated waveguide is suggested at high frequency applications and exactly it is working as same as rectangular waveguide that the sidewalls are replaced by two rows of metallic posts [8]. Therefore, The Substrate Integrated Waveguide technology usually has been used in mm-wave systems and has advantages such as high Q-factor, compact profile, low cost platform and easy fabrication [9].

Directional 3dB coupler or 90° degree hybrids have been implemented in various applications in communication circuits such as modulators, mixers, feed networks and other microwave devices. Branch line, Lange, Bethe hole, short slot and cruciform coupler are well-known conventional types of 90-degree hybrids [10].

In the last decade, various form of the SIW coupler are suggested for radar or mm-wave application for 90° phase delay such as sum-difference comparator [11], HMSIW with double-slot coupler [12], cruciform directional coupler [13] crossed-SIW directional couplers with different angles [14] and Waveguide-Hybrid Branch Line Coupler [15]. They are also noticed for 180° phase delay such as Narrow wall directional coupler [16] Half Mode Substrate Integrated Waveguide (HMSIW) for 180° phase delay [17], non-uniform width [18]. Furthermore, multi-layer SIW structures are attractive for directional coupler based on coupling from Bethe hole [19-20]. Apparently, in single layer SIW the Bethe hole made between two waveguide by the elimination of some vias.

This paper presents 3 dB H-plane SIW coupler designs for the 30-40 GHz frequency range. In order to meet the

* **CONTACT**: Mj.tavakoli@shahed.ac.ir

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challenging specifications in terms of both operating frequency and bandwidth, new multi-branch SIW H-plane couplers on a single-layer substrate are proposed. The bandwidth around 28.5% is achieved and at last, the results are compared with previous research.

2- Design Theory

The TE_{10} is known as dominate mode in the waveguide and cut off frequency define as shows in Equation 1; where a and b are selected for width and height of the conventional waveguide. c is the light speed and ε_r is the substrate permittivity [21]. The distance between the via (S) is affected on the radiation losses will create because of the leakage field in SIW structure and $S \leq 2d$ and $d \leq \lambda_g/5$ are given ideal situation where the d is the diameter of the via. The guided wavelength for the dominant mode in SIW is obtained by Equation 2 [22]:

$$a = \frac{c}{2 f_{c10} \sqrt{\varepsilon_r}} \tag{1}$$

$$\lambda_{g10} = \frac{2\pi}{\sqrt{(\frac{\varepsilon_r \omega}{c})^2 + (\frac{\pi}{a})^2}} \tag{2}$$

Multi-hole coupling structures are noticeably for enhancement of the bandwidth and coupling characteristic in directional coupler with various techniques such binomial, Chebyshev, and superimposed to calculate the coupling of each hole. In addition, many researches have been done around the effect of the number of holes on directivity and them shows that distances between the holes and hole dimensions will effect on the coupler characteristic [23]. The multi-hole waveguide coupler is employed in this design, and as shows in Figure 1 they are a few holes with uniform arrangement are modified here for the conventional directional coupler. This method is a useful technique for improving the bandwidth of the coupler.

However, the best dimension of the hole is obtained for diameter of $\lambda_g/4$ and for wideband structure the λ_g is obtained by Equation 3 where λ_{g1} and λ_{g2} are for upper and lower frequency:

$$\lambda_g = \frac{\lambda_{g1} + \lambda_{g2}}{2} \tag{3}$$

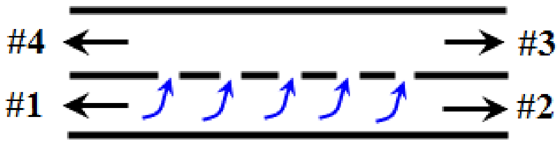

Figure 1. Multi-hole coupling structure.

The even and odd modes or mode matching method can be used for modeling the SIW coupler [24-25]. However, for common design, the length of each branch is assumed $\lambda_g/2$ and the width of the aperture is λ_g [16].

3- The Coupler Design

Figure 2 (a) shows the basic model of the 3 dB SIW coupler with Symmetrical dimensions [26]. Here, TE_{10} is the dominate mode so each branch of the coupler is working as a conventional rectangular waveguide and widest aperture is modified for coupling between top and bottom waveguide and the step shape of the waveguide at center part is used for matching. The frequency band of the waveguide determines the size of the waveguide by Equation 1. The diameter of the via is chosen to be equal or smaller than a tenth of the wavelength of the maximum operating frequency for less linkage loss.

Figure 2 (b) shows the geometry of the prototype directional coupler for MM wave application.

The taper microstrip line is used for matching connecting of the SIW part to50Ω feed with bent line. It is a common method for wideband SIW line [27-28]. Thus, the width and length are chosen so that the input impedance of the microstrip feed line matched to the SIW input impedance. Figure 2 (c) shows the geometry of the prototype feed line with taper formation.

A prototype 3dB SIW symmetrical coupler is designed by replacing the single hole by the multi section structures. Figure 2 (b) shows the designed 3dB coupler geometrical dimension for 30-40 GHz. The coupler is designed on a Rogers RT/Duroid 5880 substrate. The height of the substrate is 0.508 mm with (loss tangent 0.0009) with total dimension of $38.973 \times 93.33\ mm^2$. In addition, all dimensions have been presented in Table 1.

As described in pervious part, we have two essential parts in our design. At first based on the dominate mode, the dimensions of the waveguide are calculated and assumed the initial value of the λ_g of the center frequency. In the second part, we should modify the structure and connect it to SMA connector with matching taper line.

In the E-plane branch-line coupler, the branch parts are between the broad walls of the main waveguides so there is a plane of symmetry through the centers of the broad walls of all the waveguides.

It reduces the aperture sizes and thus increases the distance between apertures that are later to be manufactured by via holes. Finally, fine optimizations for the 3 dB coupler are required to ensure that all dimensions fall into the possible range of via holes. Combining the E-plane, multi-branch line coupler and the main directional coupler that is introduced above, lead to wideband directional coupler.

Table 1. The geometry of the prototype coupler.

parameter	mm	Wavelength
L_1	7.7	1.14 λ_{g0}
L_2	14.6	2.16 λ_{g0}
L_3	30.48	4.68 λ_{g0}
L_4	2.06	0.3 λ_{g0}
L_5	4	0.6 λ_{g0}
L_6	10	1.48 λ_{g0}
L_7	14.8	2.19 λ_{g0}
W_1	4.6	0.68 λ_{g0}
W_2	3.9	0.57 λ_{g0}
W_3	16.452	2.43 λ_{g0}
W_4	3	0.44 λ_{g0}
W_5	1.2	0.17 λ_{g0}

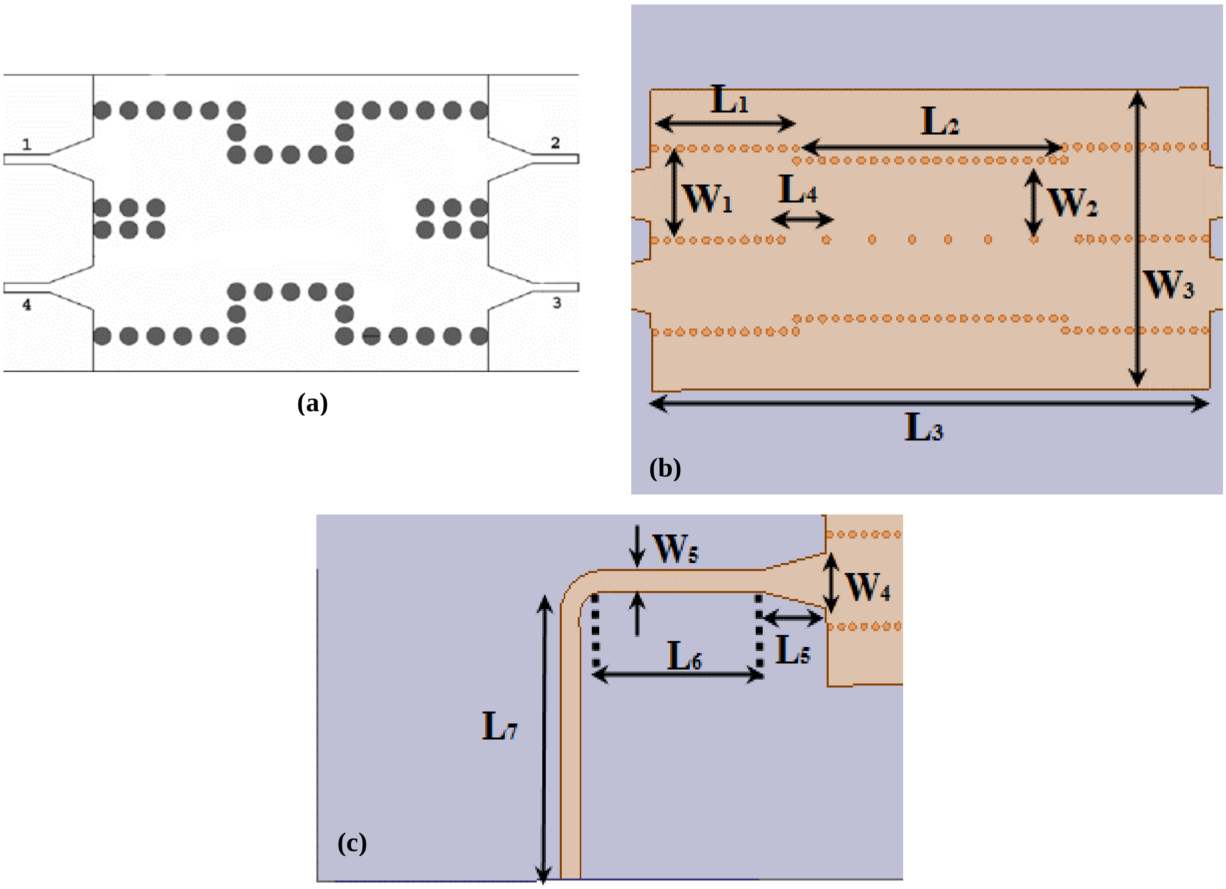

Figure 2. Geometry of the coupler (a) primary SIW coupler (b) the prototype SIW coupler (c) the final prototype coupler.

4- Simulation Results

The design parameters tuned finely by using three-dimensional (3-D) electromagnetic (EM) simulation software high frequency structure simulator (HFSS) to achieve wide band performance. In the first step, we designed conventional branch line coupler without multi hole and then the result is compared with final directional coupler when the multi hole techniques are implemented. Figure 3 shows a comparison between the suggested model of coupler in the presence and absence of the vias. As shows here, for S_{11} (reflection factor) are around -16 dB in the range of 31-37 GHz for simple model and when the vias are implemented, the result is improved and S_{11} is reduced to -40 dB and bandwidth enhanced and increased. In this case, the coupler is covered range of 30-40 GHz as shows in Figure 3 (a). Figure 3 (d) shows that we have similar condition for S_{14} (Isolation factor) and the return loss value and bandwidth is increased drastically.

For S_{12} (through factor) is around -3 to -4 dB in the range of 30-37GHz for simple model and when the vias are implemented, the result is improved and the bandwidth enhanced and increased. In this case, the coupler is covered range of 30-40 GHz as shows in Figure 3 (c) with -3 to -4 dB loss. Figure 3 (d) shows that we have similar condition for S_{13} (coupling factor) and the return loss value is around -3.8 to -4.8 dB for 30-40 GHz.

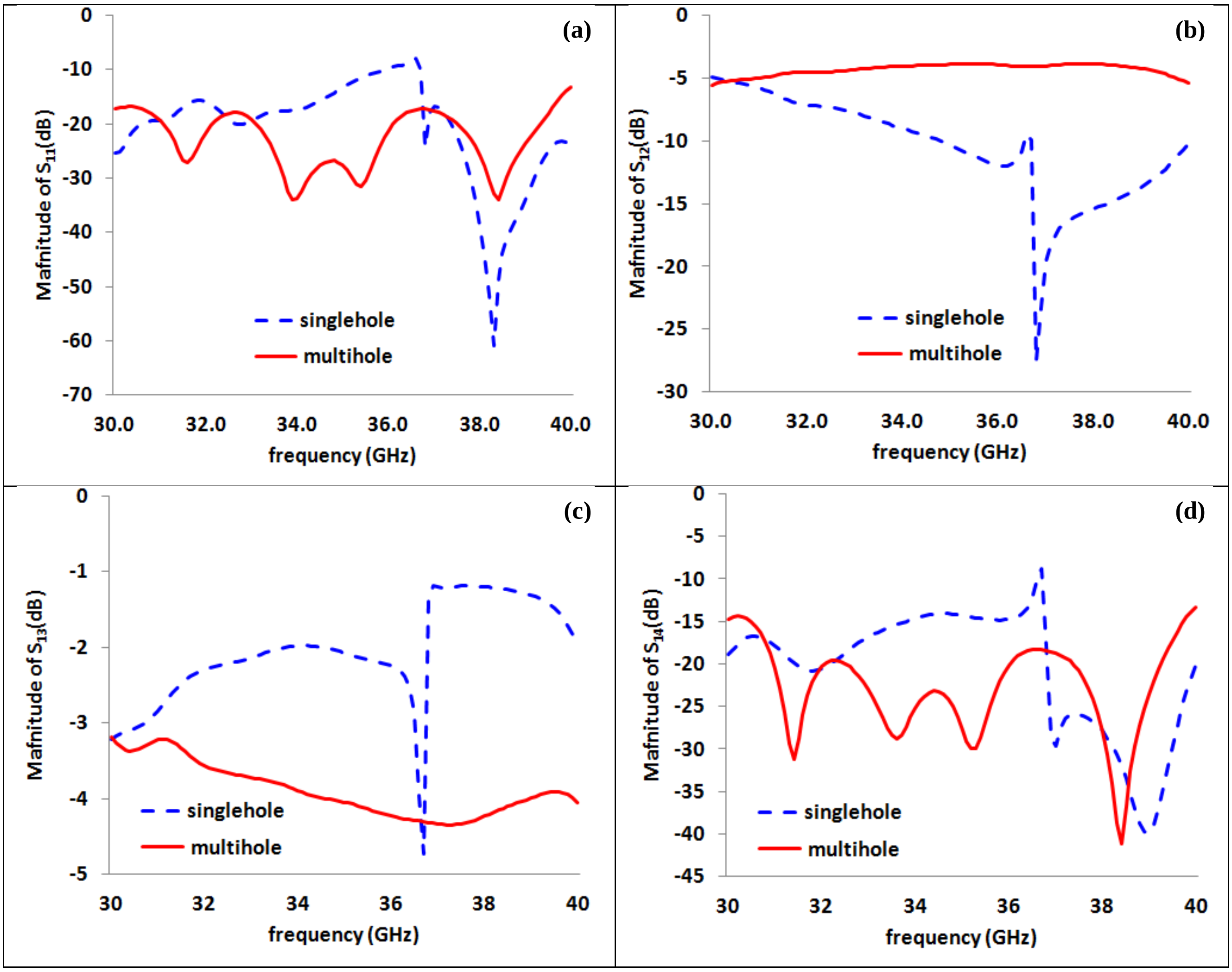

Figure 3. Comparison between suggested model of coupler in presence and absence of the vias (a)S11 or reflection factor (b) S12 or through factor (c) S13 or coupling factor (d) S14 or Isolation factor.

Figure 4 shows the phase difference between two output ports with single-hole and with multi-hole techniques. It can be seen the outputs at ports 2 and 3 are -3.8 dB to -4.5 dB, respectively, the phase difference is distributed in the range of 88.3 ~ 92.5° within the frequency band of 30 to 40 GHz.

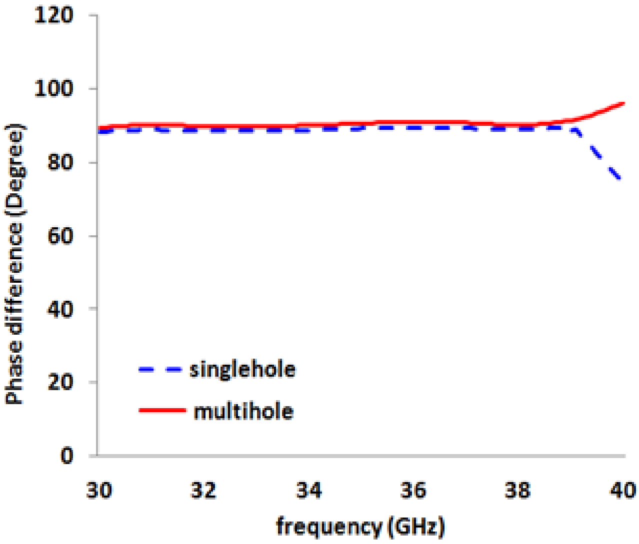

Figure 4. **Simulated phase difference between output ports for both case study of the prototype coupler.**

Figure 5 shows the current distribution at 35 GHz on the surface of the prototype coupler. It is found that the input signal from port 1 interacts with metallic posts in the hole region, and is coupled equally to port 2 and port 3. We show the current distribution for single hole and multi-hole method at Figure 5 (a) and (b) respectively.

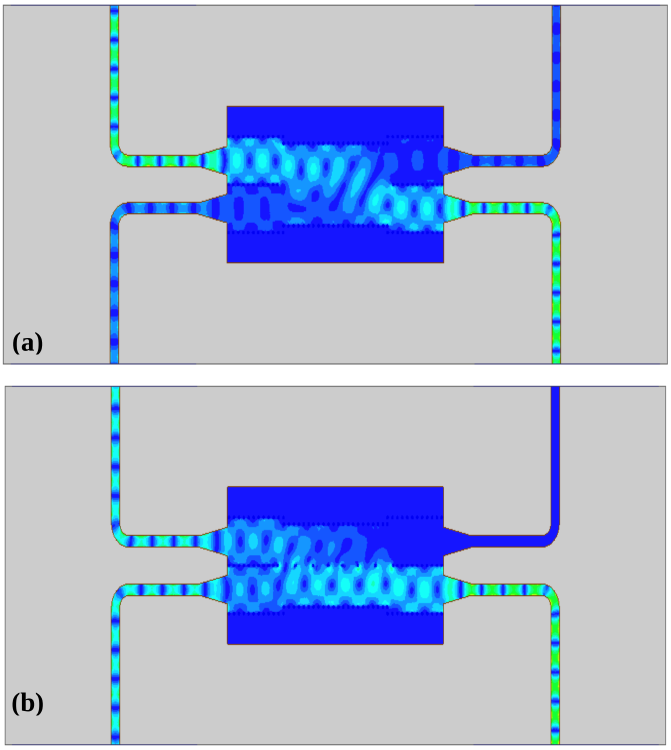

Figure 5. **Simulated current distribution at 35 GHz for (a) single hole model (b) multi hole model.**

5- Comparison

This structure is noticed in many researches of the symmetrical form and reciprocal response [13] however asymmetric forms are studied in pervious researches [25]. In the other multi- hole are noticed for improving the resulting bandwidth [24, 29]. In this section, we presented a comparison between current work and pervious models of the SIW coupler and the comparison is given at Table 2.

We have noticed bandwidth and S_{12} as important values and on the other hand, compared phase and length of them in wavelength. In addition, we are noticing the structure as a symmetric or asymmetric structure and denoted them by (S) and (A) in Table 2.

Table2. Comparison of the prototype coupler.

Reference	Bandwidth (%)	Phase/Type	S_{12}
Present model	28.5 %	90º/S	-2.5 to -4.5 dB
[10]	35 %	90º/S	-4 to -5.5 dB
[11]	13 %	90º/S	-2.5 to -4 dB
[12]	14.2%	90º/S	-4 to -4.5 dB
[13]	18%	90º/S	-3 to -4 dB
[14]	22%	90º/S	-3 to -5 dB
[15]	1.7 %	90º/S	-3 to -5 dB
[16]	5.4%	180º/S	-3.7 to -4.5 dB
[17]	19%	180º/A	-3 to -5 dB
[25]	25%	90/A	-4 to -5 dB

6- Conclusion

Broadband directional coupler in SIW technology is presented for MM wave-band applications. The specifications towards tight coupling and broadband performance require several stages in the design process. In order to overcome higher-order mode excitation commonly observed in the upper frequency range of components with tight coupling, the design process is done to place them out of operational range. The performance of the proposed coupler for 3 dB demonstrates good agreement between HFSS and CST simulations. However, the results for the through and coupled ports show additional losses between 2.5 dB and 1.3 dB. Although these are good results in the 30 GHz frequency range, the main contributions to loss appear to because by the microstrip-to-SIW transition and the dielectric substrate.

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